



Prepared for:

Rijkswaterstaat RIZA

Proposal to implement the rainfall  
generator method in river management

Report

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# I Introduction

## I.1 Aim of this project

In the last couple of years a new, more physically based, method has been developed to estimate the statistics of extreme river discharges: the rainfall generator method (RGM). An important application of this method is planned to be the derivation of the design discharges of the Dutch parts of the rivers Rhine and Meuse.

In order to prepare for the implementation of this method in river management, RWS RIZA has asked WL | Delft Hydraulics (WL) to investigate which actions are required in order to actually get the RGM accepted in practice. This report describes the results of this investigation (Chapter 2).

One of the actions already foreseen is the analysis of the reliability of the resulting discharge statistics from the RG instrument. In 2004 a definition study has been carried out in which we proposed a method for reliability analysis (Passchier et al., 2004). In the present study this proposed method is further refined (Chapter 3).

## I.2 Approach

This study has mainly been carried out by gathering information, opinions and suggestions from specialists in river management, hydrology/hydraulics and statistics. Concerning the actions required to implement the RGM in river management the following persons have been consulted:

- Ard Wolters (DWW),
- Herbert Berger (RIZA),
- Houcine Chbab (RIZA),
- Jos Dijkman (ENW, WL), and
- Herman van der Most (ENW, WL).

The method for reliability analysis has been discussed with

- Matthijs Kok (ENW, HKV),
- Albrecht Weerts (WL),
- Henk van den Boogaard (WL),
- Adri Buishand (KNMI), and
- Jules Beersma (KNMI).

The findings of this investigation have been presented and discussed in a meeting with the following participants: Hendrik Buiteveld (RIZA), Emiel van Velzen (RIZA), Marcel de Wit (RIZA), Herbert Berger (RIZA), Adri Buishand (KNMI), Jules Beersma (KNMI), Matthijs Kok (HKV), Hermjan van Barneveld (HKV), Ferdinand Diermanse (WL), Jaap Kwadijk (WL) and Hanneke van der Klis (WL). The conclusions of this meeting have been included in this report.

### **1.3 Project team**

The work has been carried out by Hanneke van der Klis. The project has been managed and reviewed by Jaap Kwadijk.

## 2 Aiming for implementation of the rainfall generator method

In this chapter we discuss successively the present status of the RGM, the objective with this instrument, the obstacles recognised and the proposed actions to realise the objective. The information in this chapter has been based on interviews with several specialists in Dutch river management (Section 1.2) and on the conclusions of the final meeting of this project.

### 2.1 Where we are now

From 1996 onwards RIZA and KNMI have worked together to develop an instrument for generating long series of synthetic discharges, both at Lobith (Rhine) and at Borgharen (Meuse). This has led to the rainfall generator method, which actually is a chain of physically based hydrological and hydraulic models. The input of the hydrological models is provided by a rainfall generator for the entire river basin.

Several studies have been carried out on separate models, on the weather generator in particular, as well as on the complete instrument, like the study on extremely high water levels on the Niederrhein (Lammersen, 2004).

Although various analyses have been carried out already, the instrument has no official status yet in Dutch river management. Knowing this, it is interesting to notice the perception and expectation on the rainfall generator instrument of the specialists we have interviewed. All of them know that in this instrument the physics have been modelled explicitly. Some of the specialists expect the method reduces the uncertainty in the return levels of high discharges, where others are sceptical about this.

Several specialists mentioned that the naming of the method is somewhat confusing, since it does not represent the complete instrument: it does not make clear that it is all about river discharges. It is advised to find another name for the method. In this report, however, we hold on to the name 'rainfall generator method' (RGM).

### 2.2 Where we want to go

RIZA aims at acceptance of the RG instrument as an approved method in Dutch river management. Determination of the design discharges at Lobith and Borgharen is considered to be one of the important applications of the method. In first instance, i.e. concerning the hydraulic design conditions of 2011, a combination of the RGM and the current method (i.e. direct statistical extrapolation of discharge measurements (Van den Langemheen and Berger, 2002)) is foreseen. On the long term it might be possible to fully replace the current method by the RGM.

Other possible applications of the RG instrument result from its possibility to analyse the influence of changes in the river basins on the statistics of extreme discharges. Among other things, this is relevant to study the homogeneity of discharge measurement series. The following examples have been mentioned:

- The RGM enables the analysis of the influence of flooding in Germany and Belgium on the return levels of high discharges at Lobith and Borgharen. The conclusions can lead to adjustment of the discharge statistics.
- The effect of changes in the river basins, like deforestation or cultivation, can better be analysed.
- The effect of climatic changes, like changing precipitation patterns or temperature rise, on the return levels of high dischargers in the Netherlands can be analysed.
- All kind of detention measures and other flood protection measures can be analysed in terms of scenario studies.

Finally, an important opportunity offered by the RG instrument is the analysis of the shape of the (extremely) high discharge waves. This potentially improves the current assumptions concerning the wave shape, as currently examined in a parallel project (report expected in 2006). Knowledge of the shape of discharge waves is relevant to, for instance, deriving the design water levels along the Dutch rivers and to study options for detention ponds. Furthermore, such information is required in testing the strength of the dikes and in analysing flooding patterns after a dike breach. These last purposes might become more important in the coming years, considering the current discussion on the Dutch safety policy concerning flooding. The tendency is to define safety standards in terms of flood risks, in which also the strength of dikes and the volume of the flood waves gain importance.

## 2.3 What hinders us from going there

Generally, the reliability of the RGM is expected to be sufficient for comparative and scenario studies. However, using the method to derive the official design discharges comes across (sometimes considerable) objections concerning the yet unknown reliability of the results. This reliability not only is unknown, also the expectations of it vary. Where some expect the resulting discharge statistics according to the RGM to be more reliable than the current statistics, because of the physics taken into account, others consider it possible for the reliability to be even smaller, because of all the uncertainties in the weather generator and the numerical models.

The specialists interviewed mentioned the following aspects as (most) important sources of uncertainty in the RGM:

- A relatively small period of about 40 years of available rainfall measurements serves as the basic information for the much longer synthetic rainfall series (typically 10.000 years). To many, this seems to be a degradation compared to the present method which is based on a discharge series of about 100 years.
- The method of generating synthetic rainfall series is such that no higher daily rainfall samples occur than measured in the base period. It is not understood how this method can lead to realistic extremes in the rainfall pattern, resulting in scepticism.

- From the synthetic rainfall series the discharge series are derived through a chain of numerical models. Each of these models represent, by definition, simplifications of reality, leading to all kinds of uncertainties. Especially the HBV models (i.e. the rainfall-runoff models) are considered to be uncertain.
- The flooding of areas in Germany and the return flow from those areas into the river should be modelled correctly. Concerning the SOBEK model, this part is considered to be the most important source of uncertainty. Moreover, since this flooding causes a considerable reduction of the high floods, this source of uncertainty might dominate uncertainties in the rainfall-runoff models and in the weather generator.

Some concerns result from lack of knowledge of the RGM, especially concerning the method used in the weather generator. Although much information and foundations of the method have been published in international scientific papers, a more easily readable explanation oriented at its application in river management is missing.

## 2.4 What we need to achieve our goal

Based on the findings described in the previous section and on the interviews we found three elements required to achieve our goal (as described in Section 2.2), namely the acceptance of the RG instrument as an approved method in Dutch river management. These elements are:

- a description of the method, the assumptions and the foundations of the RG instrument that is suitable for non-experts in Dutch river management and policy,
- the analysis of the reliability of the discharge statistics that result from the RGM, and
- a balanced communication plan to promote the RG instrument.

### Description for non-experts

As previously mentioned, part of the scepticism towards the RGM seems to be caused by lack of suitable information. RIZA is currently working on an overview report, describing the current status of the RGM. Besides this report, we advise to write a paper (e.g. for the Dutch journal  $H_2O$ ) that is suitable for non-experts in the field of river management. We mention some requirements:

- assume only basic knowledge of statistics,
- focus on the end result, namely the return levels of extremely high discharges,
- emphasize the benefits of this method compared to the current method,
- in Dutch, and
- think of a more recognisable name for the RG instrument.



## Reliability analysis

Based on the interviews we advise to carry out a thorough reliability analysis on the end results of the RGM, i.e. the return levels of (extremely) high discharges at Lobith and at Borgharen. This analysis will lead to all kinds of questions and discussions which cannot all be foreseen. Therefore, we advise to define a project team of specialists on statistics, hydrology and hydraulics. By having regular discussions on the progress of the analysis and on new insights, supported by simulation results that quantify sensitivities and uncertainties, the reliability analysis will contribute to the process of gaining acceptance of the RG instrument. To guarantee the quality of the results national or international experts on the subject could be asked to review the reliability analysis. In the next chapter we discuss this subject in more detail.

## Communication plan to promote the RG instrument

Each of the specialists interviewed emphasised that there is no guarantee that their suggestions are actually enough to get the RGM officially accepted. This is due to the fact that the final decisions have to be made by the policy makers and ultimately politicians. Thus, all depends on timing, persons and other policy issues that run in parallel. Nevertheless, the following suggestions have been made:

- For policy makers, generally non-experts in statistics and numerical models, it will be enough to give a simple description of the method, with emphasis on its benefits (and the disadvantages of the current method). An example of a disadvantage of the current method is the sensitivity of the design discharge of the Meuse for new measurements of high discharges. Furthermore, an advantage of the new method might be that the subject 'uncertainties' seems to become more important in assessing the hydraulic boundary conditions of 2011.
- Policy makers will like to know the consequences of changing the method in terms of safety, costs, international agreements, etc. The new method will more easily be accepted if the results are similar to those of the current method. In practice, it might be necessary to have the results available of the new method, before the policy makers decide. In this respect it would be useful to explain them that changing the method is not only about changing the value of the design discharge, but also another way of thinking.
- For the policy makers issues concerning the reliability of the results are not relevant as long as this is verified and approved by specialists, in particular the ENW.

The specialists advise to start active promotion of the RGM among the policy makers in 2006/2007, that is, after the hydraulic design conditions of 2006 have been determined. At that time new plans and ideas will be gathered and discussed concerning the official hydraulic boundary conditions in 2011.

If in the mean time a situation occurs in which the new method can be presented, attention must be paid to the level of abstraction of the presentation. It is crucial to approach the right people at the right time from the right level of abstraction. It is wise to ask people from DWW to advice on this point.

## 3 Considerations on the reliability analysis

### 3.1 Purpose of the reliability analysis

From the previous chapter it appears that the results of a reliability analysis of the RG instrument will be accepted by policy makers as long as specialists on statistics and physics agree on them. From this we conclude that simplifications of the method for reliability analysis are acceptable as long as the specialists agree on them. Estimations (partly) based on expert judgement may also serve the purpose. This conclusion enables us to reconsider the results of the definitions study of 2004 (Passchier et al., 2004), and discuss whether simplifications are justified. This is the aim of this chapter.

Although a reliability analysis is only one of the actions required to implement the RGM in river management, it is a crucial one. That is, if it appears that the reliability of the derived discharge statistics does not satisfy the requirements, implementing the RGM will not be desired. The other way around is also true: if it is shown that the RG instrument improves the reliability of the design discharges, it serves the confidence in the results of the RGM and underpins the ambition of RWS to implement it as an approved method.

### 3.2 Discussion of uncertainties

The end result of the RGM is a synthetic time series of the discharge at Lobith or Borgharen of an arbitrary length. Based on this time series, the return levels of (extremely) high discharges are estimated by fitting an appropriate extreme value distribution function to the discharge peaks in the synthetic time series. Realising this, together with the fact that the RGM is formed by a chain of physical models, the reliability of the return levels is influenced by the following elements:

- the weather generator, which generates synthetic time series of rainfall and temperature on various stations in the river basin based on measurements at the same stations,
- the rainfall-runoff models (i.e. HBV-models) of the partial river basins which determine the discharge contributions to the main river, based on the synthetic rainfall and temperature time series from the rainfall generator,
- the hydraulic models which determine the discharge series in Lobith or Borgharen, based on the discharge contributions calculated by the HBV-models,
- the statistical analysis which determines the return levels of the extreme discharges based on the discharge time series calculated by the hydraulic models, and
- the particular assumptions and adaptations made to couple all models and to make the RGM computationally stable.

These elements together result in the overall reliability of the estimated return levels. The definition study of 2004 (Passchier et al., 2004) extensively describes the uncertainties involved in the first three elements and their relative importance. These considerations and accompanying references will not be repeated here. Furthermore, of the hydrological and the hydraulic models we described which method is suitable to estimate the effect of each of the important uncertainties on the model results (which in fact form partial results of the RG instruments). Finally, the definition study shortly describes how the reliability analyses of each of these three models can be combined to examine the reliability of the calculated discharge series at Lobith or Borgharen.

Now, we focus once again on the chain of models that form the RG instrument, in order to propose the steps required to analyse the reliability in the discharge statistics. Notice that a reliability analysis will not result in *the* reliability of the end results. The system is that complex and the uncertainties that many that in practice a reliability method will always contain simplifications and assumptions based on expert judgement. This does not change the fact that the present state of knowledge of the models and of reliability analysis enables a well underpinned estimate of the overall reliability.

To analyse the reliability of the results of the RG instrument we suggest to follow roughly the approach proposed by Passchier et al. (2004). We suggest the following adjustments, which we further discuss below:

- analyse the sensitivity of the choices made in the weather generator to the discharge statistics,
- limit the analysis of uncertainties in the HBV-models to those sub basins that cause the main part of the river discharge,
- analyse the sensitivity of uncertainties in the SOBEK model to the discharge statistics, and
- neglect the uncertainties in the statistical analysis of the synthetic discharge series.

### **Sensitivity analysis of weather generator**

An important question concerning the reliability of the end results of the RGM is to what extent the synthetic rainfall series represent the statistics of the current rainfall patterns. Since we are interested in extremely high discharges, not only statistical quantities like the mean and standard deviation of the rainfall are of importance, but also the extreme percentiles. The modelling choices within the weather generator that are potentially relevant in this have been discussed by Passchier et al. (2004). We advise to discuss the relative importance of those choices, supported by relevant quantitative information from simulations carried out with the complete RG instrument. Furthermore, we advise to carry out this sensitivity analysis in a project team with both specialists on rainfall and specialists on river discharge, in order to combine the knowledge of both disciplines and to assure the focus on the final discharge statistics.

Some of the characteristics of the synthetic rainfall series are due to the chosen approach for the weather generator, namely the nearest neighbour method. Specialists could give a reflection on the effect of this choice on the resulting discharge statistics.

The set of most important uncertainties will be incorporated in the overall reliability analysis of the RGM. The method to do this should as much as possible correspond with the method used for the analysis of the uncertainties in the hydrological and hydraulic models.

### **Sensitivity analysis of SOBEK models**

Three different SOBEK models exist that can be chosen to use within the RGM: one model assuming infinitely high dikes in Germany, thus preventing flooding, and two versions of a model that does include flooding in Germany. The end results of the RGM will be highly influenced by the choice of the model.

In case of the model that does not include flooding, the contribution of this hydraulic model to the uncertainty in the overall results of the RGM is expected to be relatively small. The reliability of the water levels of this model is estimated to be in the order of a decimetre, while the travelling time of the flood waves is generally assumed to be well modelled. Therefore, to analyse the reliability of the overall results, the influence of the uncertainties in this hydraulic model can be neglected.

On the other hand, the models that include the flooding introduce other sources of uncertainties that might be significant to the resulting discharge estimates in Lobith. Furthermore, due to flooding high discharge waves are significantly reduced, thus potentially affecting the relative importance of uncertainties in the weather generator and the HBV-models. In order to investigate this, we suggest a sensitivity analysis. Based on the outcomes it can be decided whether the uncertainties in these hydraulic models should be taken into account or not.

### **Select most relevant HBV models**

The uncertainty in the HBV-models of the RG instrument is generally seen as an important source of uncertainty with respect to the end results. Nevertheless, not all 134 HBV-models in case of the Rhine system and 15 HBV-models in case of the Meuse system are equally important. The required effort to model the contribution from the rainfall-runoff models to the overall reliability can be reduced by selecting the HBV-models of those sub basins that together contribute substantially (say 80-90%) to the total discharge in the main river. For each of the selected HBV-models we suggest a GLUE analysis is carried out, thus selecting those parameters settings that result in acceptable HBV-results.

A point of concern is the mutual dependence between the uncertainties in each of the sub basins. This is difficult, if not impossible, to quantify. We expect, however, that the influence of this dependency on the overall reliability is significant. This could be overcome by estimating the overall reliability both assuming dependency and independency, and comparing the difference. By means of expert judgement the final estimate can be obtained.

## Neglect uncertainties in statistical analysis

The reliability of the statistical analysis of the discharge series at Lobith and Borgharen is negligible compared to the other aspects. Namely, to compute return levels in the order of 1000 years discharge series of 10.000 years are produced with the RG instrument. The reliability of the return level of 1000 years based on that many samples, assuming they are perfectly representative, is relatively small. This can be underpinned by standard statistical theory. Furthermore, in case this ‘statistical uncertainty’ is still regarded to be too large, the synthetic discharge series can easily be extended.

Although we foresee that the influence of this statistical uncertainty is minor to some other sources of uncertainty, it does play an important role in analysing the sensitivity of other uncertainties. Namely, the influence of other uncertainties in the RGM on the discharge statistics can only be quantified if it is larger than the statistical uncertainty, i.e. if the influence is statistically significant.

### 3.3 Proposed approach for reliability analysis

The general approach we propose to analyse the reliability of the end results of the RG instrument is a combination of sensitivity analysis, the Monte Carlo approach and expert judgement. Before we describe the separate parts of the proposed reliability analysis, we note the following:

- A large number of simulations has to be made in order to analyse the reliability of the results of the RGM. Since the execution of most of the simulations can very well be automated, most effort will be required in obtaining all required data and models in the required format. The simulation time required for all the simulations depends strongly on the hardware system used. For example, Linux clusters are available to execute several simulations in parallel, thus saving much simulation time. In that way, the choice of the hardware on which the simulations are executed is a more important question than the number of simulations required.
- It is not possible to foresee each single detail of the method to analyse the reliability of the RGM. During the analysis new aspects will come up. Therefore, we advise to define a project team of specialists in hydrology, hydraulics and statistics who can judge and discuss the results and the assumptions and conclusions made on the way. The steps below have already been discussed with several specialists, and can therefore be used as a concrete guideline to follow.

Based on the assumptions described above, we suggest the following steps to analyse the reliability of the end results of the RGM, i.e. of the return levels of extreme discharges:

1. Analyse the relative importance of each of the uncertainties in the RGM, many of which have already been described by Passchier et al. (2004). This sensitivity analysis results in a set of uncertainties throughout the RG instrument that should be incorporated in the follow-up of the reliability study. The following actions form part of this analysis:
  - analyse the choices made in the weather generator to the discharge statistics,
  - select the most important sub basins of which the HBV-models should be part of the analysis,

- carry out a GLUE analysis for the selection of HBV-models with historical data, in order to obtain those parameter settings that result in acceptable HBV-results. Do this twice: once assuming independence between the uncertainties of different sub basins and once assuming fully dependence, and
  - carry out a sensitivity analysis on the SOBEK models that include flooding in Germany.
2. Combine the effect of all relevant uncertainties into the overall uncertainty in the discharge statistics by means of a Monte Carlo approach (see Passchier et al, 2004) and discussion in the project team. It might very well be that other techniques appear to be more suitable in this step to (part of) the uncertainties. This can only be concluded at the end of the sensitivity analysis (Step 1).
  3. Invite national or international experts on hydrology, hydraulics and statistics to review the findings of this reliability analysis. This will guarantee the quality of the approach and of the conclusions.

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